operating at a distance of 1 metre. This corresponds to **45** dB SPL on the "annoying" curve of Figure 5. The field strength used is **10** volts per metre which from equation (3), gives an *Immunity Level* ILM40 equal to **12.4** dB re 1 volt per metre.

Compare this with the *IEC 118 Draft Standard (May 1994)*, [2][17] which proposes a field strength of **3** volts per metre and severity level (with sinusoidal modulation) of **45** dB SPL. The *Immunity Level* ILM40 is 20 log(3) - (45-40)/2 = **7.0** dB re 1 volt per metre.

Summary of the Data on Immunity Levels

Table 14 gives a summary of the *Immunity Levels* ILM40 that are pertinent for choosing immunity specifications for hearing aids.

Table 14 Immunity Levels Derived from Available Data

Immunity Levels (ILM40 in dB re 1 V/m) derived from a sound pressure threshold and from the subjective measurements.

Sound Pressure Criteria	Hearing Aid Noise Specifications	Subjective Tests, Subjects with Normal Hearing		EHIMA [1] Subjective Test *
Class 1	7.4 ‡ using 3 V/m § 17.9 ‡ using 10 V/m §	> 22 6 to 17 ≤ - 3	Not Perceptible. Moderately Perceptible. Annoyingly Perceptible	1.9 ‡ using 3 V/m § 12.4 † using 10 V/m §
Class 2	37.9 ‡ using 100 V/m §	≥ 35 34 23 to 28 ◻ ≤ 22	Not perceptible. Just Perceptible Moderately Perceptible, Annoyingly Perceptible	32.4 † using 100 V/m §

§ Assumed field strength (of GSM signal) used with the sound pressure criteria.

‡ Equation 3.

† For 10% hearing aid users "annoyed".

◻ ILM40 = 28 dB was found to be "sometimes usable" but 23 dB was "unusable" for Class 2.

Given the nature of the judgments and the small number of trials, the *Immunity Levels* in Table 14 are biased on the low side of the worst case estimation being sought. For example, the direction of maximum pickup of interference will vary with hearing aids treated or untreated, so that while the head may shield one hearing aid effectively to reduce or eliminate interference it may not do so to the same extent for another hearing aid.

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[17] This standard does not specify the maximum hearing aid response when oriented with respect to the radio field, but specifies the maximum of the responses obtained by rotating the hearing aid in steps of 90° in the horizontal plane.

The proposed design criteria are based on the summary in Table 14 and must be interpreted in the light of the previous comment.

CONCLUSIONS

Proposed Design Criteria

Two levels of immunity are proposed corresponding to the levels of "tolerable interference" and "virtually no interference".

Tolerable Interference

Class 1: If interference is "moderately perceptible" it does not prevent hearing aid use, and can be expected to be "tolerable". From the subjective tests on normal hearing persons ILM40 = **11** dB[18] re 1 volt per metre is about the minimum allowable level. This is consistent with ILM40 = **12.4** dB re 1 Volt per metre of the Australian Draft Standard, and **ILM40 = 17.9** dB re 1 volt per metre derived from hearing aid noise specifications at 10 volts per metre GSM signal[19]. Therefore an ILM40 = **11** dB re 1 volt per metre is proposed for Class 1 service.

Class 2: An ILM40 of at least **28** dB re 1 volt per metre is required if the subjective tests on normal hearing persons are reasonably representative. At this level the interference was "moderately perceptible" and the *mobile telephone* could be "usable sometimes". The corollary is that this ILM40 level will not guarantee usability of a GSM telephone for all persons at all times. "Tolerable interference" for Class 2 really means that interference may occur for any particular combination of hearing aid, *mobile telephone* and person.

No Interference

Class 1: If no interference is allowed the value ILM40 = **24** dB re 1 volt per metre (23.4 dB at 10 V/m, Table 11) is sufficient to make the interference equal to the maximum hearing aid internal noise with the best microphones currently in production. No significant improvement is gained with a higher value.

Class 2: The subjective tests on normal hearing persons indicate that an ILM40 of at least 35 dB say **36** dB re 1 volt per metre is required.

---

[18] The hearing aid with 6 dB re 1 Volt per metre *immunity level* suffered annoying interference in one particular orientation.

[19] An ILM40 equal to 7.4 dB re 1 volt per metre based on the hearing aid noise specification and a GSM RF level of 3 volt per metre falls short of the proposed ILM40 level of 11 dB re 1 volt per metre.

Proposed Levels

Less confidence can be placed in the estimates for Class 2 service where the appropriate radio frequency field strength of a *digital mobile telephone* is very difficult to measure and specify. From the hearing aid noise specifications using a GSM field strength of 100 volts per metre, the ILM40 is **38** dB re 1 volt per metre, suggesting that an appropriate GSM radio frequency field strength may be in the region of 100 volts per metre. The above proposed values, rounded to the nearest whole number, are summarised in Table 15. These values should be treated as minimum standards.

Table 15 Proposed Immunity Design Criteria

Service	Immunity Levels (ILM40)	
	Minimum Standards for Tolerable Interference	Minimum Standards for No Interference
Class 1	11	24
Class 2	28	36

In Table 16, these proposals are translated into test conditions that may be used in a standard specification. Suggested test limits are shown in bold type. The test method proposed is the same as the physical measurements of this report.

Table 16 Proposed Test Limits

Service	***Severity*** Field Strength of carrier (80% 1 kHz Amplitude Modulated 900 MHz Carrier Wave) (V/m)	***Test Level*** § Equivalent Input Referred Sound Pressure (dB SPL)	
	Interference Criteria	Tolerable Interference	No Interference
Class 1	for Required ILM40 equal to (dB re 1 V/m)	11	24
	3	37	11
	10	**58**	32
	30	77	**51**
Class 2	for Required ILM40 equal to (dB re 1 V/m)	28	36
	10	24	8
	30	**43**	27
	100	64	**48**

§ Calculated from Table 15 using Equation (3).

Figure 6 shows the approximate ranges of immunity levels that correspond to above proposals.

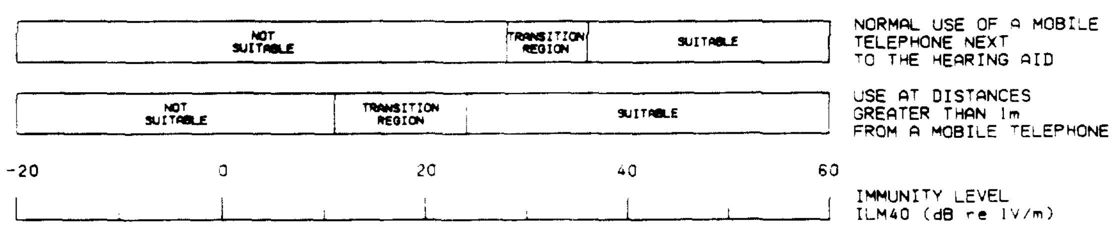


Figure 6 Immunity Level Scale, Microphone Input

5. Summary and Conclusions

The responses of Hearing aids were measured in a radio frequency field at 900 MHz in a specially designed waveguide test apparatus. One obtains significant information by positioning the hearing aid for maximum response for sinusoidal amplitude modulation of the radio frequency field. Immunity is characterised by a single number called the *Immunity Level*. Hearing aids may be designed to have a high immunity using several well-known techniques. Important observations are made concerning hearing aid and mobile telephone design and use.

SUMMARY

Measurements

A terminated waveguide was designed and constructed for measurements of GSM electromagnetic radiation in the frequency range 750 MHz to 1.12 GHz. A suitable manipulating apparatus for holding a hearing aid inside the waveguide was designed and constructed. The hearing aid is aligned for maximum response to the radio frequency field inside the waveguide using the manipulator. The acoustic output of the hearing aid, caused by the detection of the radio frequency signal was measured. The detection was the object of study.

It is shown in Appendix 3 that the waveguide provides measurements equivalent to those obtained in a radio frequency anechoic room. The waveguide may be used instead of an anechoic room which provides a free field.

The signal detected by hearing aids was measured. Hearing aids were subjected to radio frequency fields inside the waveguide with electric field strengths from 0.1 volt per metre to 200 volt per metre RMS carrier wave at 900 MHz. The carrier was 80% amplitude modulated with a 1000 Hz sine-wave. These measurements are presented in terms of a single number, the *immunity level* ILM40 for microphone input and ILT20 for telecoil input, defined as the electric field strength in dB relative to 1 volt per metre that produces an *equivalent input referred sound pressure* of 40 dB SPL, or an *equivalent input magnetic field strength* of 10 mA per metre (20 dB re 1 mA per metre), in the hearing aid when switched to microphone or telecoil respectively. Interference levels may be predicted from the response to sinusoidal modulation. Measuring the response to pulsed, radio frequency field is not warranted. The directivity of the responses varies with the orientation of the hearing aid relative to the direction of the electric field. A special manipulator was designed to get consistent and repeatable measurements, since the hearing aids needed to be oriented for maximum pickup. This direction did not remain the same when the hearing aid was subject to various treatments that reduce the response to the radio frequency field. In addition, the shape of the response was not symmetrical for rotation of 180 degrees in the plane of the electric component of the radio frequency field.

Hearing aids were treated with electrostatic shielding, metal impregnated case mouldings and capacitors fitted to shunt the radio frequency signals. These treatments resulted in significant increases in immunity from interference and it was concluded that they were independent.

The immunity required for hearing aids used "near" and "next to" a *mobile telephone* was derived from the subjective measurements, estimated radio frequency field strengths and tolerable levels of interference. These *immunity levels* are the basis of the proposed specifications.

Results

General

Almost all hearing aids measured are not immune from interference to radiation from nearby 2 watt (class 4) *hand held mobile telephones*.

None of the untreated hearing aids measured were suitable for communicating using a *handheld mobile telephone*.

Improvements Achieved

The hearing aids were "treated" with a combination of techniques to reduce their susceptibility to interference. These techniques are, not surprisingly:

- reduction of the size of the effective "antenna" in the hearing aid (by a new design) that responds to the 900 MHz radiation,
- electrostatic shielding and
- use of shunt capacitors.

Implications for Hearing Aid Design

The hearing aids measured represent most hearing aids currently in use.

As well as the above methods, it is conceivable that susceptibility to interference can be reduced by applying "circuit techniques" to the design of hearing aid amplifiers.

Modifications to existing hearing aids are not practical. Design modification to existing hearing aids in production is likely to require extensive work comparable to designing a completely new hearing aid.

The development of new hearing aid designs needs extensive use of techniques for measuring the susceptibility to interference. The waveguide equipment used in this study has been found very convenient for this purpose. Measurements are sufficiently accurate for development purposes.

CONCLUSION

Hearing Aid Design

Most hearing aids currently available are not immune to interference from nearby *mobile telephones*. Very few existing hearing aids are likely to be suitable for use with a *mobile telephone*. The proposed specifications for "tolerable" interference may be considered as a minimum standard for Class 1 hearing aids but not for Class 2 hearing aids.

Use of the proposed specifications for Class 1 and Class 2, found in Chapter 4 for "no interference" is recommended for the development and design of new hearing aids. It is strongly recommended that **all** new hearing aids meet the Class 2 requirement and be designed to have an *immunity level* (ILM40) of at least 36 dB re 1 volt per metre.

Mobile Telephone Design

Useful guidelines for Mobile telephones designed for use with hearing aids include:

- *Mobile telephones* should provide sufficient acoustic output to enable communication while avoiding acoustic feedback (in the hearing aid) caused by placing the *mobile telephone* as close as possible to the hearing aid. The radio frequency field strength to which the hearing aid is exposed is also reduced.
- The acoustic receiver should be positioned as far away from the antenna as possible sufficient for example, to maintain the effective radio frequency field strength below 100 volt per metre at full power output.
- Special attention to acoustic coupling to a hearing aid would be an advantage.
- Spurious magnetic fields must be kept low, i.e. less than about 0.3 mA per metre, if magnetic coupling for use with a telecoil is provided.

Users of Mobile Telephones and Hearing Aids

Users of hearing aids should be made aware of the possibility of interference so they can recognise it. The amount of immunity from interference should be explained and demonstrated to the user before purchase of a new hearing aid or a *mobile telephone*. This should be done in both a noisy and a quiet environment, with the mobile telephone or hearing aid that the user proposes to use.

Users of mobile telephones should be aware of the potential for interference to hearing aids (and other potentially susceptible equipment) currently being used in the community, and what they can do to reduce any evident annoyance, e.g. by moving away from hearing aid users.

Appendix 1. Terminated Waveguide Test System

Design equations are given for a waveguide in which hearing aids were measured. The waveguide comprised three sections, a short waveguide launcher for supplying power into the waveguide, a central section in which to place the hearing aid and a terminating section with absorbing material to reduce the reflected wave to a sufficiently low value.

DESIGN

The terminated waveguide test system is one means of generating a known electromagnetic field that is totally confined and, does not generate electromagnetic interference to local mobile services, in particular, the local mobile telephone services which use the same frequency band as the test system.

The design of the system was based on a US Environmental Protection Agency (EPA) waveguide electromagnetic field calibration facility and is constructed from WG4 (WR975) waveguide which has internal dimensions of 0.248 metre wide and 0.124 metre high with a useable frequency range of 750 MHz to 1.12 GHz. The system as shown in Figure 7 comprises three distinct sections:

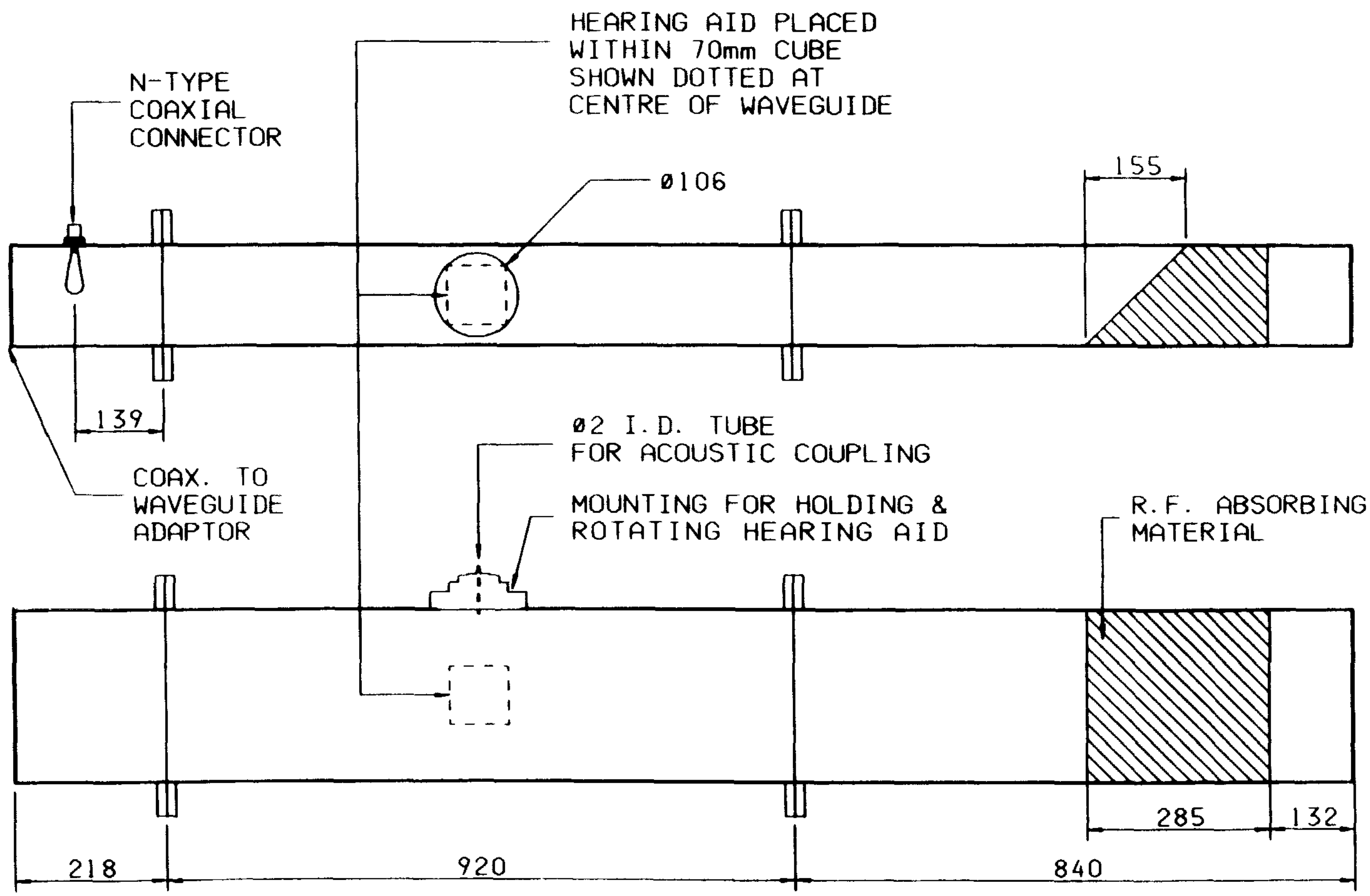
- a conventional waveguide launcher with an N-type coaxial adaptor,
- a central waveguide section to provide the working volume into which the hearing aid and manipulating device are inserted and
- a termination fitted with tapered absorbing material.

Based on the US EPA calibration facility the length of the central waveguide section was chosen to be two waveguide wavelengths at the lower end of the GSM transmit band i.e. 890 MHz.

The waveguide wavelength, λ_W, is given by (Table 17):

$$\lambda_W = \frac{\lambda_0}{\left(1 - (\frac{\lambda_0}{\lambda_c})^2\right)^{\frac{1}{2}}}$$

where λ_0 is the free space wavelength and
λ_C is the cut-off wavelength of the waveguide which for the fundamental TE_{10} mode is twice the width of the waveguide (0.496 m).



NOTES:

1. WAVEGUIDE TYPE WG4. 750 MHz TO 1.12 GHz
2. ALL DIMENSIONS ARE IN mm
3. WAVEGUIDE SECTIONS SHOWN

Figure 7 Terminated Waveguide

Table 17 Wavelength in Waveguide

Frequency (MHz)	λ_w (m)	λ_0 (m)
890	0.460	0.337
900	0.445	0.333
915	0.437	0.328

It is a fact that the waveguide wavelength is longer than the equivalent free space wavelength.

Another important parameter is the waveguide impedance Z in ohms (Ω) which, for the fundamental TE_{10} mode, refer to Figure 8, is given by:

$$Z = \frac{377}{\left(1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2\right)^{\frac{1}{2}}}$$

It is also a fact that the waveguide impedance is greater than the free space value of 377 Ω.

A knowledge of the waveguide impedance is important because it relates the magnitude of the electric field E_y in volts per metre (V/m) to the magnitude of the magnetic field H_x in amperes per metre (A/m) via:

$$\frac{E_y}{H_x} = Z$$

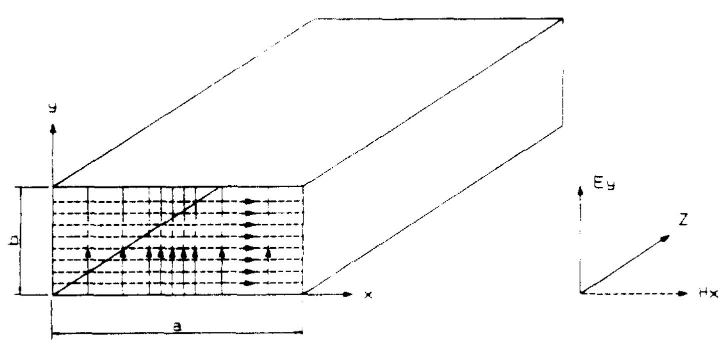


Figure 8 Waveguide Nomenclature and Field Directions for the TE_{10} Mode

As a consequence of the waveguide impedance being greater than that of free space, any electromagnetic interference (EMI) test results on hearing aids related to the magnetic field strength will need to be adjusted accordingly before a direct comparison can be made with the EMI test results obtained from free space irradiation of hearing aids.

The original design of the waveguide termination allowed for a section of tapered RF absorbing material with an overall length of two waveguide wavelengths and a half waveguide wavelength taper for the mid band frequency of the waveguide i.e. 935 MHz. However actual return loss measurements indicated that such a large section of RF absorbing material was unnecessary and a more critical factor was the position of the absorbing interface. Finally, the tapered RF absorbing material had the overall dimensions of 0.285 metre with a 0.155 metre taper. The return loss was better than 20 dB over the GSM band of 890 MHz to 915 MHz. A photograph of the terminated waveguide is shown in Figure 9.

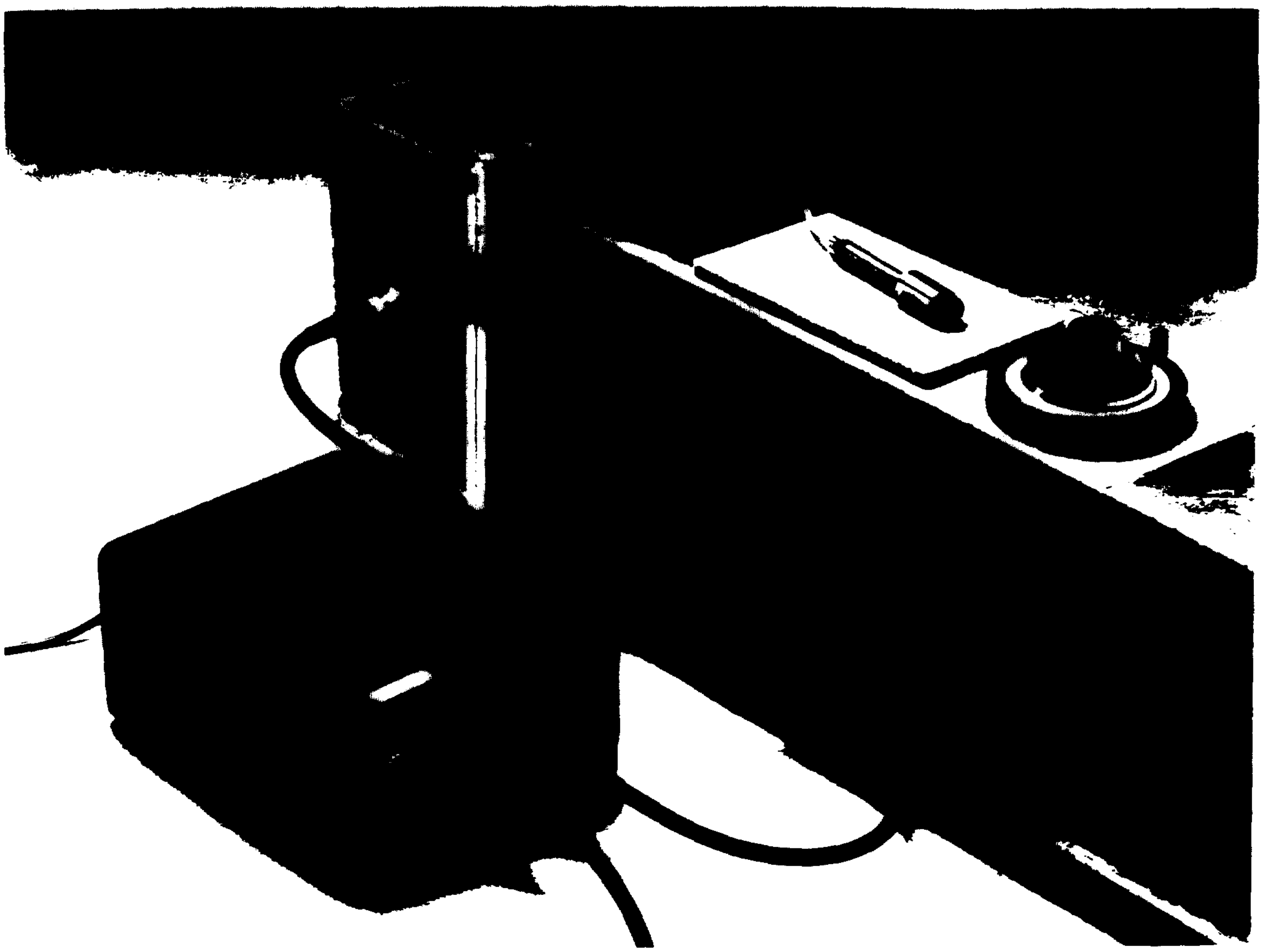


Figure 9 View of Waveguide

CALCULATION AND CALIBRATION OF WAVEGUIDE FIELD STRENGTHS

The electric field E_y in volt per metre and the magnetic field H_x in amperes per metre are calculated from the following equations:

$$E_y = \left(\frac{2ZP}{ab}\right)^{\frac{1}{2}} \qquad H_x = \left(\frac{2P}{Zab}\right)^{\frac{1}{2}}$$

where P is the power transmitted in watts,
Z is the waveguide impedance in ohms and
a and b are the waveguide dimensions in metres.

The electric fields in the waveguide were calibrated using a small dipole antenna (11 mm tip-to-tip) which itself was calibrated against a transfer standard traceable to the Australian Radiation Laboratories.

The forward and reflected power levels in the waveguide were measured using a directional coupler and power meter as shown in Figure 10.

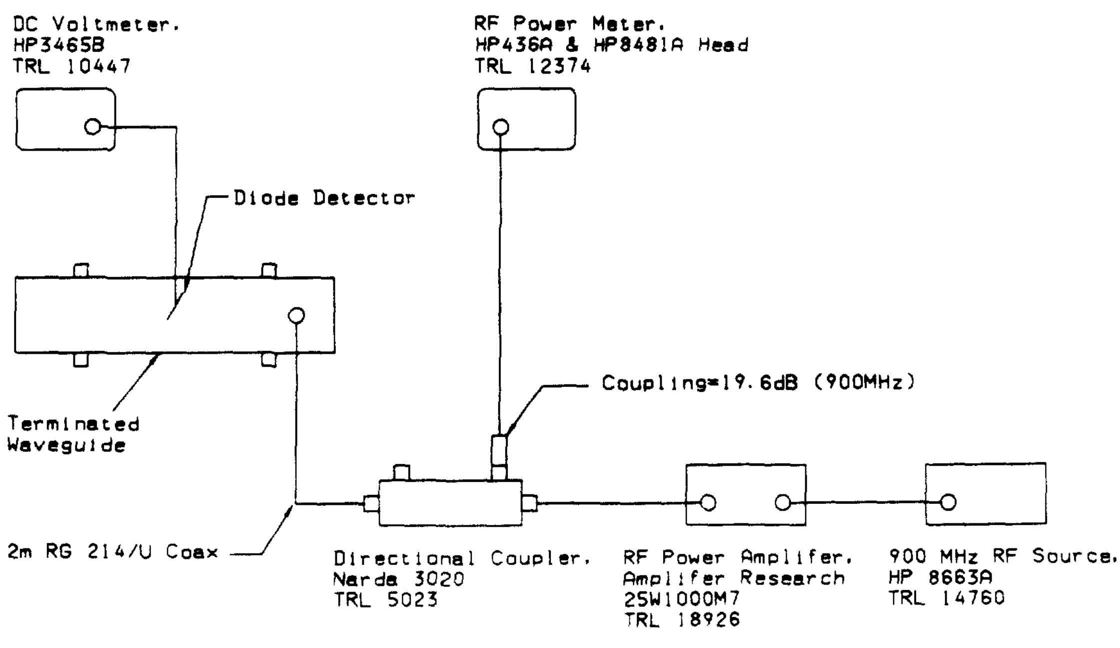


Figure 10 Calibration of Terminated Waveguide Electric Field - RF Input Power

Electric field strength values were measured for various forward power levels. These data are presented in Table 18 along with calculated power levels for the field strengths.

Table 18 Waveguide Electric Field Strength Versus Input Power Calibration Data

E-Field (V/m)	*Input Power (mW)*	
	Calculated	*Measured*
1	0.034	0.032
3	0.304	0.29
5	0.845	0.75
10	3.379	3.18
20	13.52	11.74
30	30.41	24.97
40	54.06	47.68
50	84.46	79.60
60	121.63	114.62
70	165.55	156.02
80	216.23	203.78
90	273.67	257.90
100	337.87	318.40

Appendix 2. Hearing Aid Measurements

Hearing aids used in Chapter 2 and further details of the measurements are described: (a) a description of the hearing aids, (b) the radio frequency signal generator used with the waveguide, (c) a discussion on the use of sinusoidal modulation, (d) a description of the manipulator, (e) measurement of the hearing aid acoustic output and (f) the measuring procedure. A selection of directional characteristics of hearing aids showing the variations observed is given. The responses of four hearing aids were measured from 800 to 1000 MHz.

Description of Hearing Aids Used in Experiments

Table 19 shows the hearing aids used in the measurements. Numbers in the first column refer to the photograph in Figure 11.

Table 19 Description of Hearing Aids

Reference No. in Figure 11	*Type§ (Used in Chapter 2)*	*Manufacturer*	*Model*	*Description*	*Construction Technique*
1	HPBTE	Bernafon NAL	SP675¶	High gain & Power using a CMOS amplifier¤ & separate Bipolar output amplifier.	Chip-on-Board
2	HPBTE	Phonak	PPCL4‡	High power & gain with bipolar amplifier.	Printed Circuit Board
3	MPBTE	NAL	VHK‡	Medium power and gain with bipolar amplifier.	Printed Circuit Board
4	ITE	Bernafon NAL	IT312†	Low power and gain using a CMOS amplifier¤.	Chip-on-Board
5	ITE	Phonak	9000AFSC	Low power & gain using a bipolar amplifier.	Custom
6	MPBTE	Bernafon NAL	SB13†	Medium power & gain using a CMOS amplifier¤.	Chip-on-Board
7	MPBTE	Oticon	425	Medium power using a bipolar amplifier.	Printed Circuit Board

§ Types: HPBTE High Power Behind-the-Ear
MPBTE Medium Power Behind-the-Ear
ITE In-the-Ear

¶ Not yet in production.
† On issue by AHS.
‡ Previously issued by AHS.
¤ These hearing aids use the same amplifier I.C. chip set.

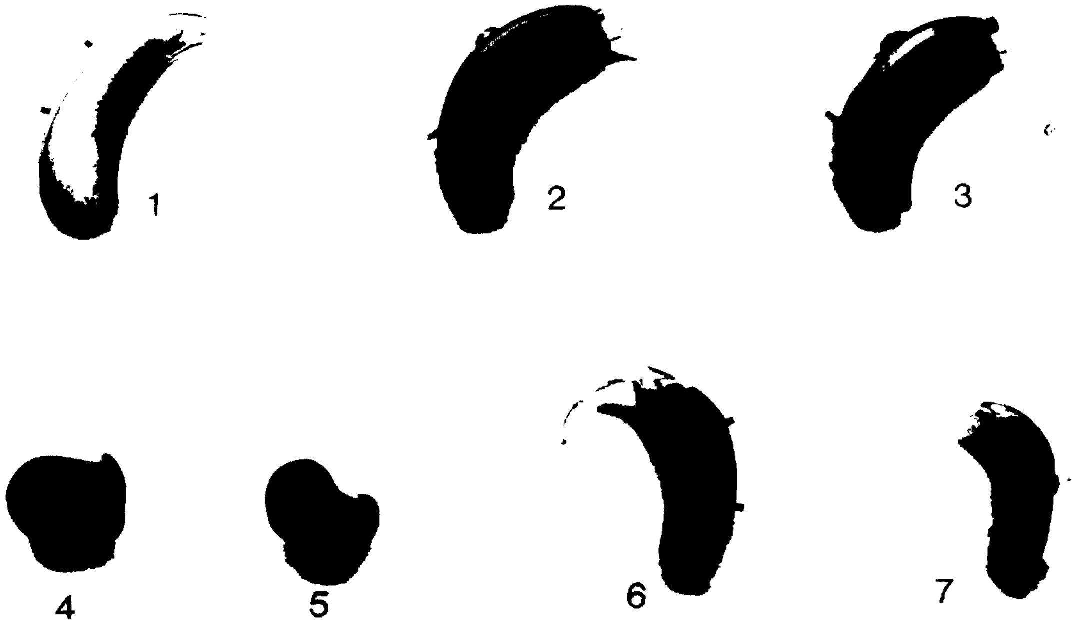


Figure 11 Hearing Aids Used in the Measurements

RADIO FREQUENCY FIELD IN WAVEGUIDE

Waveguide

A radio frequency anechoic room is the accepted standard for generating a free field radio wave. Anechoic rooms are large and expensive, making their use practical only when one is already available. The lack of convenience and cost normally precludes extensive use of such a facility by the development or design engineer. The alignment of the hearing aid must be adjusted to allow for the directional characteristics of its sensitivity to be taken into account. Special apparatus is very useful for remote manipulation to prevent the presence of an operator disturbing the RF field. The waveguide design is given in Appendix 1, and measurements indicating that it gives the same results as in a free field are presented in Appendix 3.

The size of the waveguide at the GSM frequencies enables a hearing aid to be placed inside in a relatively uniform field[20]. It may not be the most suitable approach for future systems using frequencies as high as 2 GHz. The apparatus is suitable for use on the bench in a normal laboratory environment, is convenient to use and is not influenced by laboratory surroundings.

Initial calibration data is given in Table 20, showing the generator output required for field strengths from 1 to 100 volts per metre. After the complete measuring apparatus was set up, the field strength was again measured, under computer control, using the Telecom Research Laboratories (TRL) probe over the range of generator outputs used for the tests. Figure 12 shows that the probe is not linear at high levels and verifies the earlier calibration around 10 volt per metre. The calibration constant -52.4 dBm for 1 V/m was calculated using linear regression around 10 volt per metre, where the response is linear, and was used for setting the output of the radio frequency generator for all the measurements at 900 MHz.

Table 20 Calibration of Generator and Waveguide

E Field§ *(Volts per metre)*	*Input Power (mW)*	*RF Generator 6060B Output*† *(dBm)*
1	0 032	-53.1
3	0.29	-43.8
5	0.75	-39.7
10	3.18	-33.4
20	11 74	-27.8
30	24 97	-24.4
40	47 68	-21.7
50	79.60	-19.5
60	114 62	-17.9
70	156 02	-16.5
80	203 78	-15.3
90	257 9	-14.3
100	318.4	-13.4

† Generator — Frequency 900 Mhz, Modulation off.
§ TRL Probe — Within 1 dB at 50 volts per metre using Raham Model 84C E Field Probe calibrated at Australian Radiation Laboratory

[20] A more difficult problem is presented when leads are attached for connecting accessories such as external microphones and CROS fittings. The design of these accessories must be considered as an additional problem to that addressed in this report.

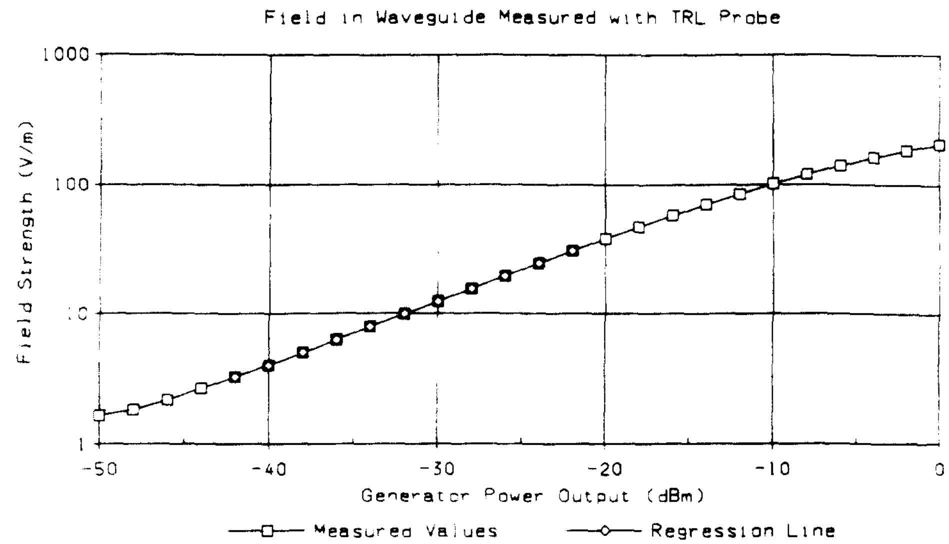


Figure 12 Field Strength in Waveguide versus Generator Output

When the waveguide was set up at NAL, the return loss with the manipulator inserted, the return loss was -14 dB at 900 Mhz and less than -9 dB from 750 to 1000 MHz. This was used for all the hearing aid measurements.

Figure 13 shows the variation in generator power required to maintain a constant field strength of 10 volts per metre from 800 to 1000 MHz. The responses of some hearing aids (discussed in a following section) were measured over this frequency range.

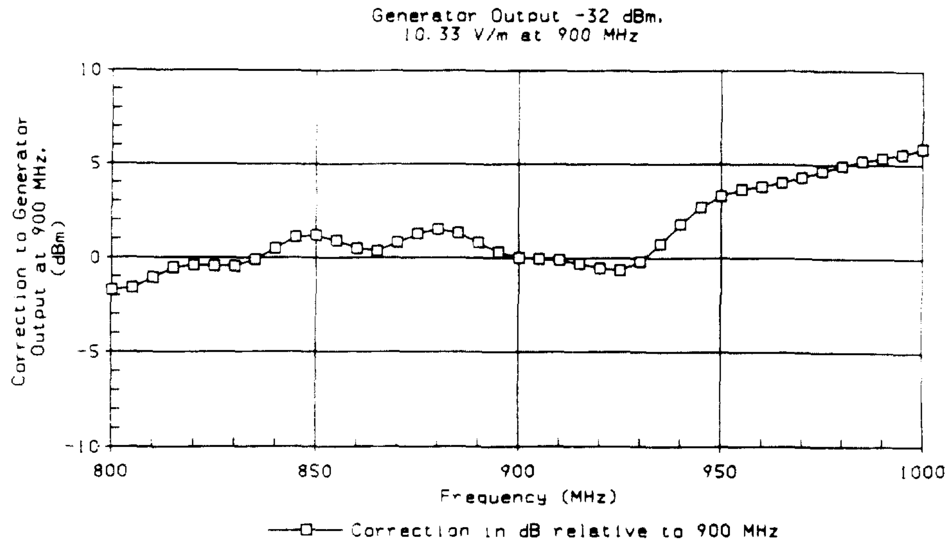


Figure 13 Generator Corrections for Constant Field Strength from 800 to 1000 MHz

Apparatus

Field Generation		
RF Generator	-	Fluke Model 6060B Synthesised RF Signal Generator
RF Power Amplifier	-	RF Devices Pty Ltd, LA200-5, 5 watt
Terminated Waveguide	-	Australian Hearing Service & Telecom Research Laboratories
Field Calibration		
Diode Probe	-	Supplied by Telecom Research Laboratories
Digital Voltmeter	-	Hewlett Packard Type 3455A Digital Voltmeter

MODULATION

Hearing aids detect the amplitude variations of the incident radio wave. Because these variations are at an audible rate[21], they are heard in the acoustic output of the hearing aid. The shape of the modulation is incidental, and determines its frequency content. Designers are interested in measuring the detection of radio frequency voltages, discussed in Appendix 4, and not the frequency content in the output of the hearing aid, whose effect may be calculated using the frequency

[21] Variations at a higher or lower frequency may still cause audible effects and improper operation of other equipment.

response of the particular hearing aid. When sinusoidal amplitude modulation is used, only one component is measured and a narrow band filter can be used to reduce the noise level. The convenience and higher signal to noise of the continuous sinusoidal modulation method makes it more practical than pulse modulation techniques. In the measurements reported here, the 900 MHz carrier was 80% amplitude modulated by a 1000 Hz sinusoid which is available on most signal generators.

This satisfies the measurement criteria given in Chapter 2, and the results can be interpreted with reasonable accuracy for pulse modulation.

GSM pulses with the same peak radio frequency power as sinusoidal amplitude modulation cause nearly the same acoustic power in the output of a hearing aid (assuming the hearing aid has a flat frequency response). If required, the frequency spectrum at the output of a hearing aid can be predicted with reasonable accuracy from the hearing aid response at 1000 Hz, without the need to measure more than one spectral peak, necessary with pulse modulation.

When pulses are used, at least 6 of the spectral components are significant[4], and requires the hearing aid frequency response to be specified. The total output (weighted or unweighted) could be measured but high noise levels and difficulty of direct interpretation in terms of the detected signal make this method unsatisfactory.

MANIPULATOR

A gimbals style mounting was designed to rotate the hearing aid about three axes to enable it to be oriented at any angle in the waveguide relative to the electric field. The apparatus is shown in Figure 15. Inside the waveguide it is constructed of PTFE, except for nylon screws used for bearings and mounting the structure to the base, and polyester actuating cord. A BTE hearing aid is clamped to a tray using mounting clamps designed to hold it firmly in the centre of the waveguide. "BlueTac©" was sufficient to hold ITE type hearing aids in place. Photographs Figure 14 and Figure 16 show the arrangements used for ITE and BTE hearing aids respectively.

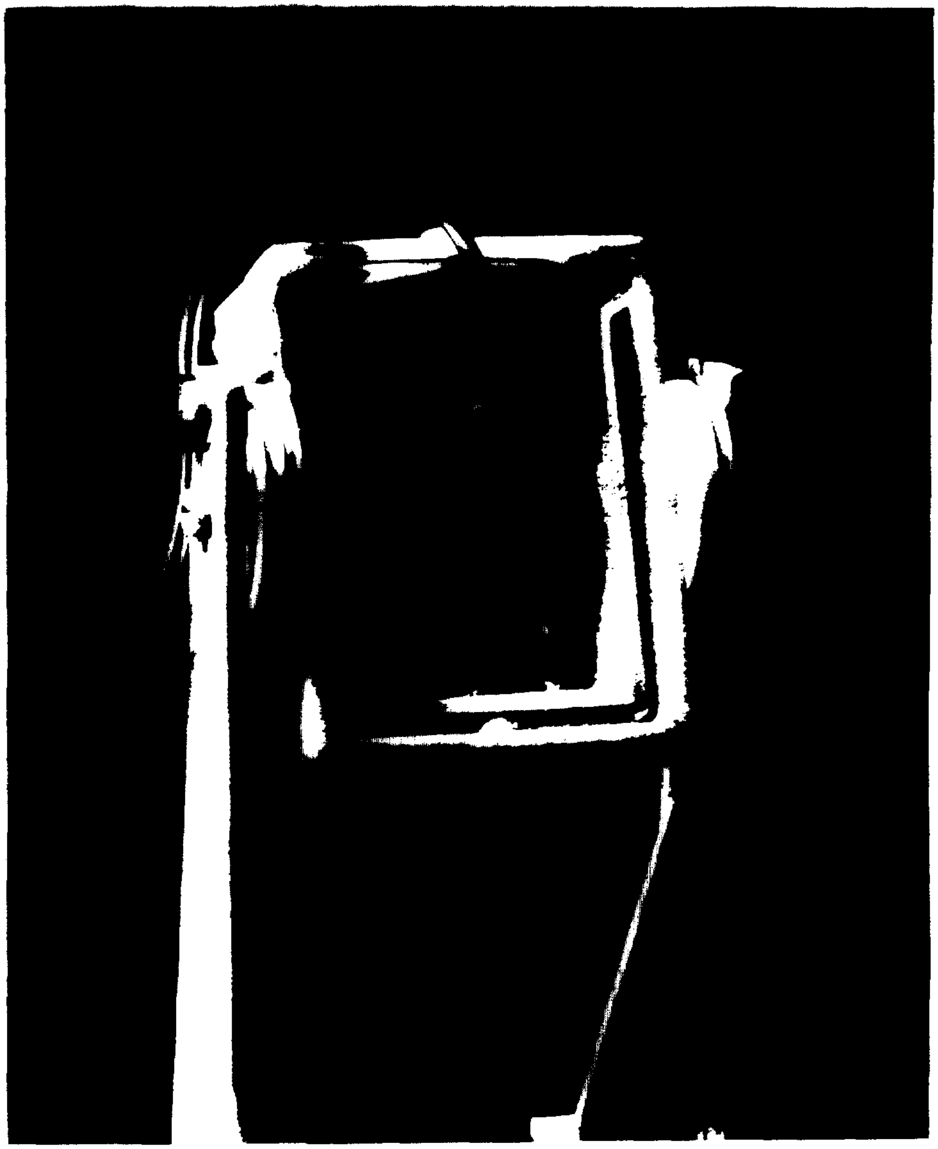


Figure 14 Typical Mounting of an ITE Type Hearing Aid

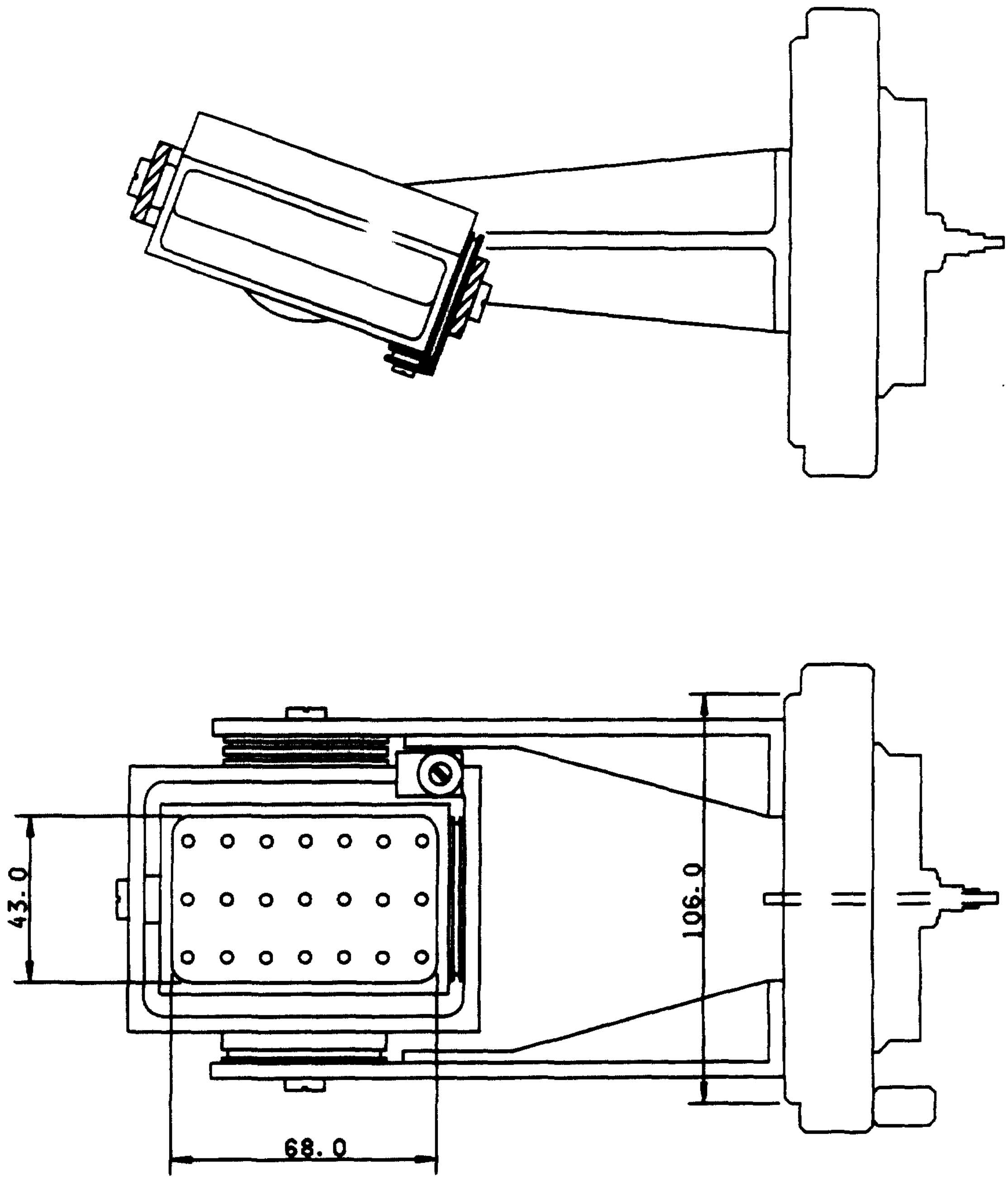


Figure 15 Manipulator Detail

Figure 16 Typical Mounting of a BTE Hearing Aid